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Solid state stabilization of proteins by sugars

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Inulin, a flexible
oligosaccharide II:
Review of its
pharmaceutical
applications

4

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ABSTRACT

Inulin is a flexible oligosaccharide which has been used primarily in food for decades. Recently new applications in the pharmaceutical arena were described. In a previous review¹ we described the physicochemical characteristics of inulin, characteristics which make inulin a highly versatile substance. Here, we review its pharmaceutical applications. Applications of inulin that are addressed are stabilization of proteins, modified drug delivery (dissolution rate enhancement and drug targeting), and lastly physiological and disease-modifying effects of inulin. Further uses of inulin include colon specific drug administration and stabilizing and adjuvating vaccine formulations. Overall, the uses of inulin in the pharmaceutical area are very diverse and research is still continuing, particularly with chemically modified inulins. It is therefore likely that even more applications will be found for this flexible oligosaccharide.

INTRODUCTION

Inulin is a fructan-type oligosaccharide that can be found in a wide range of plants.² It was discovered in the 19th century³ and since then its characteristics has been investigated extensively. Most commercially available inulin is extracted from chicory root, which contains a relatively high concentration of this carbohydrate.⁴ Inulin has proven to be a versatile substance with a large number of different applications mainly in food and pharma. In a previous review, we addressed the physicochemical properties of inulin that make it such a widely applicable compound.¹ Processing history and degree of polymerization have a large impact on the physicochemical behavior of inulin. As physicochemical behavior governs functionality for different applications, these characteristics should be taken into account when using inulin.

Some examples of saccharides frequently used as excipient in pharma are glucose, sucrose, trehalose, lactose, dextran and cellulose.¹ Inulin differs from these saccharides in molecular weight and/or the type of glycosidic bond between monomers. Inulin has a higher molecular weight than mono- and disaccharides, with that it has a higher glass transition and melting temperature, and is more viscous when dissolved. The higher molecular weight also correlates with a lower solubility. Compared to other oligo- and polysaccharides, inulin has a high molecular flexibility because of its (2→1) linked-d-fructosyl backbone. Therefore inulin has relatively low glass transition and melting temperatures compared to other oligo- and polysaccharides. These characteristics can be both advantageous and disadvantageous depending on the application at hand. Unlike most of the other mentioned saccharides, inulin is not metabolized by humans. This allows for unique applications such as determination of kidney function and colonic targeting, which makes use of metabolization by microbiota present in the colon. Reducing groups of saccharides are undesired for many pharmaceutical applications. When presence of reducing groups is a concern, inulin is more suitable as an excipient than for example glucose and lactose.^{1,5}

Over the past decades, more and more research on food and pharmaceutical applications of inulin has been published. The approval of the Generally Recognized As Safe (GRAS) status of inulin by the United States Food and Drug Administration in 2002 seems to have provided a boost to research into applications of inulin.⁶ As inulin's food applications have been reviewed before we will not discuss them here.¹ To our knowledge, only one review has been published in which pharmaceutical applications of inulin are addressed amongst other topics.⁷ In this chapter, an overview will be given of the current pharmaceutical applications of inulin in the light of its physicochemical characteristics. Applications which will be addressed are stabilization of proteins, modified drug delivery (dissolution rate enhancement and drug targeting), and physiological and disease-modifying effects of inulin.

PHARMACEUTICAL APPLICATIONS

STABILIZATION

Anhydrobiosis

In nature, inulin has been associated with drought protection in several plants, with increased levels of inulins found in stress resilient plants.^{8,9} Membrane stabilization is believed to be an important part of the drought protection of inulin.⁸ Vereyken *et al.*¹⁰⁻¹³ have published several papers on the mechanism of stabilization of fructans on membranes. They investigated the effects of inulin on model systems, such as: phospholipid monolayers, bilayers and liposomes in states varying from dry to completely hydrated. Fructans (inulin- and levan-type) were found to increase lamellar repeat distance and reduce vesicle fusion during air drying, indicating they were present between the lipid bilayers.¹¹ Fructans insert between the headgroups of several glyco- and phospholipids even if the lipid packing is very tight.^{10,12,13} Fructan immobilized the lipid headgroups through direct interaction, but increased mobility of the acyl chains because the insertion of fructan caused them to be spaced further apart, in turn leading to a lower order-disorder phase transition temperature.¹⁰ Additionally, fructan reduced the accessibility of the membranes, indicative of some form of coating of the membrane.¹³

The effect of fructans on the membranes was much stronger than that of other polysaccharides such as dextran, which was explained by inulin's more hydrophobic character.¹³ Inulin showed more interaction with the headgroups than levan-type fructan.¹² This is probably because inulin inserts more deeply into the membrane compared to levan.¹⁰ Increasing molecular weight of inulin was found to correlate with stronger interactions with the membranes.¹² Levan-type fructans perform worse than inulin-type fructans despite the fact that they are much larger. Apparently, some other trait of inulin must be the reason for its success. The flexibility of inulin's molecular backbone, conformation of the backbone as well as hydrophobicity were suggested as explanations for inulin's effects on these membranes.^{11,12} Additionally, inulin's furanose groups are also smaller and more flexible compared to pyranose groups found in dextrans.

Hincha *et al.*^{8,14-16} also investigated membrane stabilization by oligosaccharides including inulin using liposomes as model systems. During freeze-drying inulin stabilized large unilamellar vesicles of egg phosphatidylcholine, whilst hydroxyethylstarch (HES) did not stabilize them at all. A combination of inulin and glucose was especially effective.¹⁵ Based on findings with raffinose-family oligosaccharides, it was concluded that a higher degree of polymerization (DP) provides increased protection of liposomes against fusion at elevated temperatures and against leakage after rehydration, because of the higher glass transition temperature (T_g) of longer chain oligosaccharides.¹⁴ A larger chain length resulted in better membrane stability during air drying when inulin-type fructans were used, but not when

glucans were used.¹⁶ Glucans were however increasingly effective at reducing membrane fusion with increasing chain length, contrary to inulin.¹⁶ The limited solubility of larger inulin (DP >10) caused it to precipitate during the used slow air-drying and prevented it from stabilizing the liposomes.⁸ In agreement with the findings of Vereyken *et al.* discussed above, Hinch *et al.* also found a direct interaction of inulin with the phospholipid in the dry state and a reduction of the gel to liquid-crystalline phase transition temperature.^{15,16}

Livingston *et al.* (2007)⁸ have provided an in-depth review on abiotic stress tolerance in plants by fructans. It shortly describes current, more general theories on how (oligo)saccharides stabilize membranes, mainly the vitrification theory and the water replacement theory. The water replacement theory explains how sugars stabilize membranes by replacing the hydrogen bonds of water with the membrane during drying and thereby inserting into the lipid bilayer.¹⁰ Overall, it seems that inulin's characteristics, the structural flexibility of the backbone and furanose groups, conformation, and hydrophobic-hydrophilic balance allow it to interact with the membranes better than other oligosaccharides as described above. Inulin's flexibility in particular allows it to overcome the steric hindrance which usually inhibits sugar-membrane interactions.^{8,11}

The vitrification theory states that sugars form glasses instead of crystals during drying. The viscosity of a glass is extremely high, resulting in practically no diffusion and restricted molecular mobility of the membranes. A kinetically stable glass is the result. The glass should remain amorphous, as crystallization would lead to a loss of protein-sugar interactions. Clearly, a higher T_g then correlates with better stabilization.⁸ Therefore, vitrification alone cannot explain the stabilizing effect of fructan¹⁷⁻¹⁹, as other oligosaccharides with even higher T_gs, such as dextran and hydroxyethyl starch, did not provide better stabilization. Both vitrification and water replacement are needed for stabilization.¹⁹ Inulin is unique in its ability to vitrify as an oligosaccharide, whilst maintaining a good interaction with the membrane as if it was a smaller saccharide, thus combining requirements for both the vitrification and water replacement theories.

Protein stabilization

The mechanisms behind membrane stabilization in nature and protein stabilization in the pharmaceutical arena are very similar, with the vitrification theory and water-replacement theory also being applicable to protein stabilization.^{19,20} Recently, the role of these two different mechanisms under different conditions was investigated.²¹ It was concluded that if the T_g of a sample is at least 10-20 °C above storage temperature, water replacement is the predominant mechanism of stabilization. However if the T_g is lower, vitrification limits stability.²¹ In other words, if the T_g is high enough to immobilize the protein, the amount of interaction between the sugar and the protein determines its stability, yet if the T_g is too low, the (lack of) immobilization becomes the limiting factor.

Other physico-chemical characteristics of sugars required for good stabilization are low hygroscopicity, low crystallization rate and little or no reducing groups. For freeze-drying a high Tg of the maximum freeze-concentrated solution (Tg') is also desired. Compared to trehalose, which is a frequently used protein stabilizer, inulin has similar hygroscopicity, it crystallizes less rapidly and the longer chain inulins have higher Tg and Tg' values.¹ Additionally, higher molecular weight inulin has fewer reducing groups, a higher glass transition temperature and with that a lower tendency to crystallize for example when exposed to ambient moisture. This being given, it is not surprising that inulin was shown to be a good stabilizer of proteins under various conditions and stresses. Inulin has been successfully used to stabilize proteins during spray-drying²¹⁻²³, freeze-drying (lyophilization)^{5,24-28} and spray-freeze drying.^{23,28,29} However, inulin does have some reducing groups, limiting its applicability to some extent.³⁰ The number of reducing groups is dependent on processing and DP and is generally limited.¹

Inulin, trehalose and dextran have been identified as suitable cryo- and lyoprotectants for the major constituent of influenza subunit vaccine, i.e. haemagglutinin (HA), meaning they all stabilized HA during freezing and freeze-drying.³¹ During storage of 4 different model proteins after lyophilization, inulin was a better protein stabilizer than a similar-sized dextran.⁵ The storage temperature was well below the Tg of the formulations to allow for optimal vitrification. Water-replacement was therefore considered to be dominating protein stability. It was suggested that inulin encountered less steric hindrance than dextran when interacting with the protein, because of inulin's higher molecular flexibility. Lyophilization of alkaline phosphatase without stabilizer reduced its activity to around 5%, but when either inulin, trehalose or glucose was added, full activity was maintained.²⁴ When added to bovine plasma protein, inulin also reduced denaturation during freeze-drying similar to sucrose and glucose, with an optimal concentration of 10% w/v.^{26,27}

During spray-freeze-drying, spraying a solution into liquid nitrogen followed by freeze-drying, HA stabilized with inulin in hepes buffer was not structurally altered and it did not lose its antigenetic properties.^{23,28} When PvdQ, acyl-homoserine-lactone (AHL) acylase, was spray-freeze-dried, mannitol, trehalose and inulin all fully maintained its activity.²⁹ Inulin has also been applied as a protein stabilizer during hot-melt extrusion, in which a polymer based product for the controlled release of protein is created. As lysozyme is a relatively thermostable protein³², no degradation was found during extrusion at 55 °C. It was however suggested that for a more labile protein, inulin could also provide protection to the heat stress induced by this process.³³

The main goal of the various processes described above is to achieve a product that is stable over time. Table 4.1 provides an overview of reports on inulin's stabilizing effect on dried proteins during storage under various conditions. Tonnis *et al.*⁵ reported degradation kinetics of their 4 model proteins during storage (60 °C, <10% RH, 28 days), but not the remaining

Table 4.1. Overview of reported storage stabilities of proteins dried with inulin and other sugars.

Protein	Protein: Sugar Ratio (w/w)	Prepa- ration	Storage conditions			Activity/Potency loss after storage		Article cited
			T (°C)	RH (%)	t (days)	Stabilizer	Loss *	
PvdQ	1:100	SFD	20	<10%	28	Inulin DPn 23; trehalose Mannitol Liquid control (after 7 days)	None Some None	²⁹
AP	1:9	FD	20	0	28	inulin DPn 6**,14,23 glucose, trehalose No stabilizer	None None Complete	²⁴
AP	1:19	FD	20	0	105	Inulin DPn 23, trehalose	None	³⁴
HA	1:47	FD	20	0	182	Inulin DPn 6, DPn 14 Trehalose, dextran56kDa No stabilizer	<20% <20% Complete	³¹
HA	1:200	SD,SFD	20	10	1085	Inulin DPn 23 Liquid control 4°C	None Complete	²³
AP	1:9	FD	20	45	28	Inulin DPn 14,23; trehalose Inulin DPn 6 Glucose No stabilizer	No ~25% ~50% Complete	²⁴
AP	1:9	FD	20	60	28	Inulin DPn 14,23; trehalose inulin DPn 6; glucose No stabilizer	None ~50% Complete	²⁴
PstI	n.r.	AD	37	n.r.	7	Trehalose Maltotriose Inulin; dextran ***	none 80-90% complete	³⁵
HA	1:47	FD	45	11	28	Inulin DPn 14 Inulin DPn 6 Trehalose Dextran 56kDa No stabilizer	38% 24% 23% 65% 89%	³¹
HA	1:47	FD	45	11	182	Inulin DPn 6,14; dextran 56kDa; no stabilizer Trehalose	Complete 20%	³¹
PvdQ	1:100	SFD	55	<10%	28	Inulin DPn 23;trehalose Mannitol Liquid control (after 7 days)	No Complete Complete	²⁹
AP	1:9	FD	60	0	6	Inulin DPn 14,23	~50%	²⁴

Table 4.1. *Continued*

Protein	Protein: Sugar Ratio (w/w)	Prepa- ration	Storage conditions			Activity/Potency loss after storage		Article cited
			T (°C)	RH (%)	t (days)	Stabilizer	Loss *	
						Inulin DPn 6; trehalose; glucose; no protectant	Complete	
AP	1:1-1:20	SD	60	≤6%	19	Inulin DPn 23 Trehalose	30% 10%	²¹
DNase	1:11	FD	60	0	42	Sucrose; trehalose; inulin DPn 14, 23	~20%	³⁰
						No protectant	~65%	
AP	1:19	FD	60	0	90	Inulin DPn 23 Trehalose	20% None	³⁴
AP	1:19	FD+T	60	0	105	Inulin DPn 23 Trehalose	25% Complete	³⁴
DNase	1:11	FD	85	0	42	Trehalose Inulin DPn 14, DPn 23 Sucrose; protectant	~50% ~70% Complete	³⁰

AP=alkaline phosphatase, DNase = recombinant human DNase, HA = Haemagglutinin, Lys=Lysozyme, PstI = restriction enzyme PstI, PvdQ = acyl-homoserine lactone acylase PvdQ ; AD = air dried, FD=Freeze-drying, SD= Spray-drying, SFD=Spray-Freeze-Drying, T= Tableting, C= Crystallization. n.r. = not reported

*If loss is listed as none, no significant loss was detected

** Inulin DPn 6 can also be referred to as oligofructose

*** Degree of polymerization/molecular weight was not reported

activity after storage. Their results are therefore not included in this table, the reader is directed to that article for further information.

At room temperature inulin proved to be an equally good or better stabilizer than other saccharides. With increasing relative humidity, inulins with a higher DP perform better. This is likely because those inulins have a higher intrinsic glass transition temperature and can thus absorb more water before this lowers the T_g of the mixture to below the storage temperature. The relatively small inulin with DP 6, also called oligofructose, caused a loss of activity of around 50% in alkaline phosphatase. That degradation may have been induced by the relatively high amount of reducing groups in that particular inulin sample. This level of degradation was not found with the other, larger inulins tested.²⁴ When lyophilized alkaline phosphatase formulations with trehalose were compressed into tablets, the very brief exposure to atmospheric moisture and compacting forces resulted in formation of trehalose anhydrate crystals, leading to a complete loss of activity of the incorporated protein within 1 week of storage at 60 °C, 0% RH. In contrast, inulin remained amorphous

and maintained 75% activity of the protein after 3 months of storage at 60 °C, 0% RH. In fact, inulin did not even crystallize when stored at 60 °C, 33% RH for two days.³⁴ PvdQ spray freeze dried with mannitol stored at 55 °C also resulted in crystallization of the sugar, leading to a complete loss of activity.²⁹ Inulin and dextran were unable to maintain activity of air-dried samples of restriction enzyme PstI stored at 37 °C.³⁵ It is most likely that limited solubility of inulin caused it to precipitate during this slow drying process, in turn preventing it from stabilizing the protein as was also seen with air-dried liposomes.⁸ Unfortunately, the authors did not report the DP of the inulin, which influences its solubility.³⁵

At elevated temperatures, the stabilizing capacities of different saccharides vary. As mentioned above, if vitrification is sufficiently achieved, the stabilizer with most interactions with the protein is likely to stabilize best. Oligosaccharides, however, are more sterically hindered than smaller mono- or disaccharides, reducing their interactions with the protein.⁵ Inulin's molecular flexibility is able to compensate this to some extent, unlike the more molecularly rigid dextran.^{5,31} Thus depending on the storage temperature and the Tg of the sample, a longer chain length of the oligosaccharide (resulting in a higher Tg) could be beneficial if vitrification is lacking, yet it could also have the opposite effect if more protein-sugar interaction is needed. As mentioned inulin has a small amount of reducing groups, meaning some protein degradation because of the Maillard reaction might occur. Yet even under extreme storage conditions (85 °C, 0% RH, 42 days) this only played a minor role in protein stability of rhDNase, a protein that is sensitive to this type of degradation.³⁰ In summary, inulin is a good stabilizer of proteins in the dry state, and depending on the formulation and storage conditions it can be better than smaller sugars.

Other stabilization

Apart from membranes and proteins, inulin has also been used to stabilize several pharmaceutically relevant systems. For example, (PEGylated) liposomes, polyethylenimine based polyplexes, lipoplexes^{36,37}, polymersomes³⁸, influenza virosomes with and without encapsulated plasmid DNA³⁹, whole inactivated influenza virus⁴⁰, recombinant adenovirus⁴¹, and Δ^9 -tetrahydrocannabinol (THC)^{42,43}.

This variety of applications shows that under the appropriate conditions inulin may provide stabilization against chemical degradation (e.g. THC) as well as against physical degradation (e.g. lipoplexes). Inulin fully protected PEGylated lipoplexes against aggregation during lyophilization and 3 months of storage thereafter, whilst dextran did not.³⁶ Inulins were also preferred as stabilizer over dextran for various other types of PEGylated nanoparticles due to their compatibility with PEG.³⁷

In preserving physicochemical characteristics of doxorubicin-loaded (PEG)₃-PLA nanopolymerosomes during lyophilization, inulin was found to be superior over trehalose, sucrose, mannitol, lactose, polyvinylpyrrolidone, and several other excipients.³⁸ Inulin also

fully preserved influenza virosomes during lyophilization. Compared to a liquid dispersion, the powder had substantially prolonged preservation of potency and in case of influenza virosomes with encapsulated plasmid DNA transfection activity.³⁹ A combination of mannitol and inulin improved the therapeutic applicability of a recombinant adenovirus during freeze-drying and storage.⁴¹ Lastly, incorporation of THC in an inulin matrix by lyophilization strongly increased its stability.⁴³ Spray-freeze drying THC with inulin turned out to provide even better stabilization than freeze-drying, likely because of the much faster cooling rate.⁴² Inulin might therefore also be an interesting stabilizer for other unstable drugs.

DRUG DELIVERY

Solution behavior alteration

Solution rate enhancement

For oral drug administration, drugs need to be dissolved before they can be absorbed by the intestinal membrane. Therefore, the bioavailability of drugs with low aqueous solubility (Biopharmaceutics Classification System class II and class IV drugs) is usually poor because they slowly dissolve in the gastro-intestinal track. One of the strategies that can be applied to increase the dissolution rate is the production of a solid dispersion that is composed of a hydrophilic carrier in which the drug is finely dispersed. When this soluble carrier dissolves rapidly, the poorly soluble drug is hydrated faster, resulting in faster dissolution. Inulin has been used to produce solid dispersions of various poorly soluble drugs.⁴³⁻⁴⁶ Solubility of inulin is much better than these drugs and is dependent on the molecular weight of inulin, with smaller inulins having a higher solubility.⁴⁷

Dissolution behavior of solid dispersion tablets made of diazepam in inulin was significantly better than those based on dispersions with disaccharides like sucrose or trehalose.⁴⁴ It was found that the dissolution rate of the disaccharides was extremely high, resulting in supersaturation of diazepam in the near environment of the dissolving tablet, causing it to subsequently precipitate into large crystals with obviously detrimental consequences on the release profile. This uncontrolled crystallization did not occur for inulin included diazepam, due to its lower dissolution rate.⁴⁴ Figure 4.1 illustrates the difference in release profiles of the sugars and diazepam for trehalose and sucrose formulations, and the similar release profiles for the solid dispersions of inulin and diazepam.

However, using fenofibrate as model drug, the dissolution behavior of the inulin based solid dispersion tablets at high drug load (50% (w/w)) was poor, probably also due to recrystallization of the incorporated drug during dissolution. This disadvantage could be circumvented by the incorporation of superdisintegrants, croscarmellose sodium or sodium starch glycolate, in solid dispersion.⁴⁶ Similar solid dispersion tablets based on polyethylene glycol 20K and polyvinylpyrrolidone K30 also exhibited excellent dissolution behavior, but were outperformed by those based on inulin after they were stored for 3 months at

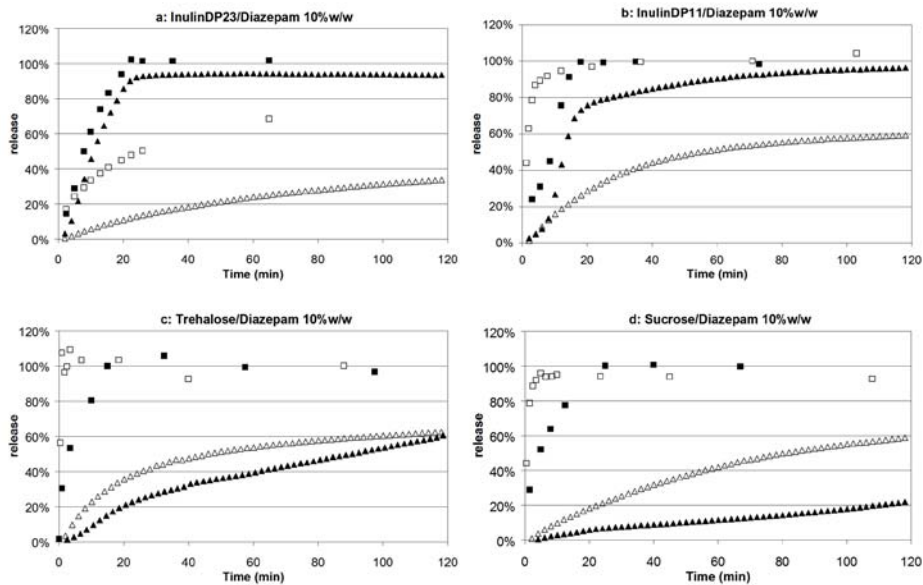


Figure 4.1 Dissolution of tablets prepared from solid dispersions and physical mixtures containing 10% w/w diazepam prepared with different sugars: (a) inulin DP23, (b) inulin DP11, (c) trehalose, (d) sucrose. (Key: ■: sugar from solid dispersion, ▲: diazepam from solid dispersion □: sugar from physical mixture, △: diazepam from physical mixture) (n=3 tablets, all s.d.< 10%)⁴⁴

20 °C, 45% RH or 40 °C, 75% RH.⁴⁶ Release of TMC240, an HIV protease inhibitor, was improved both *in vitro* and *in vivo* after oral administration due to incorporation in a solid dispersion of inulin.⁴⁵ Lyophilization of nifedipine with relatively low concentrations (up to 10%) of inulin directly in gelatin capsules increased dissolution rate, but as dissolution measurements were not carried out under sink conditions the overall dissolution enhancement was limited.⁴⁸

Inulin improved the dissolution of irbesartan in a physical mixture, with gradually increasing dissolution rates with increasing inulin content. Chemically modified poly(acrylic acid) grafted inulin was less successful at increasing dissolution behavior for irbesartan.⁴⁹ Another chemically modified form of inulin tested for dissolution rate enhancement is Inutec SP1. It is an inulin with alkyl groups grafted on primary or secondary hydroxyl groups of the polyfructose backbone and acts as a polymeric surfactant.^{50,51} Itraconazol was incorporated in a solid dispersion of Inutec SP1 via spray drying and hot-stage extrusion. Even though phase separation was found and part of the itraconazol was crystalline, the dissolution behavior of the solid dispersion was better than that of itraconazol alone.⁵⁰ It was later shown that spray dried itraconazol and Inutec SP1 showed no interaction and addition of

an itraconazol compatible polymer was needed to obtain a molecular dispersion.⁵¹ Contrastingly, when solid dispersions with high drug loads were produced by spray freeze-drying, Inutec SP1 was found to have superior dissolution behavior compared to inulin and polyvinylpyrrolidone.⁵²

Amorphous unmodified inulin has been shown to be a suitable filler-binder for tablet production, with chain length dependent disintegration time.⁵³ It was also possible to produce tablets from freeze-dried inulin formulations, in which case preconditioning of the inulin powder at 45% RH prior to tableting produced the best tablets.³⁴ It was also possible to make a tablet for sublingual administration of poorly soluble THC based on a solid dispersion with inulin.⁴³ For regular delivery to the GI tract, dissolution of 80% of the drug in around 20-30 minutes is normal, whereas sublingual formulations require a dissolution time of a few minutes at the most. The inulin based sublingual formulation showed complete release within around 3 minutes.

Modified release

Inulin could be used to alter the release profile of lysozyme from a hydrophilic multiblock copolymer aimed at prolonged release, because inulin acted as a pore-former.³³ Some studies have also been published in which drugs are encapsulated with inulin or chemically modified inulin for prolonged release.^{54,55} Acetylation of inulin strongly reduces its solubility (in a buffer of pH 7.4). Additional succinylation can then be used to increase solubility, allowing control over solubility and with that the release profile of microspheres from this material.⁵⁴ Microspheres of this modified inulin produced by solvent precipitation showed a porous interior and different particle size distributions for the different drugs used.⁵⁴ Chymotrypsin containing microspheres, with a particle size distribution from 0.5 to 4 μm , showed release for up to a week with a release of nearly 70% at the first time point of 24 hours. Chlorhexidine containing particles were significantly larger, i.e. 90-130 μm , and showed a similar burst release, followed by a release rate that was slower than the chymotrypsin microspheres.⁵⁴ Overall, the prolonged release is limited, since most of the drug is released in the initial burst.

Inulin, inulin acetate (inac) and inulin acetate associated with 1,12-dodecanedicarboxylic acid (inac-dia) were used in the encapsulation of serine protease inhibitors using coacervation, producing particles with a size ranging from 0.5 to 5 μm .⁵⁵ Inulin and inac microspheres showed a burst release of around 60% in the first minutes of dissolution, with a controlled release of the rest of the dose over a period of 4 days. Inac-dia displayed an initial burst release of only 32% after 15 minutes, but showed an additional burst release of around 30% after about 1.5 days due to erosion, followed by prolonged release similar to the inulin and inac spheres.⁵⁵ Another example of controlled release with a chemically modified inulin is the chemical coupling of inulin to ibuprofen using N,N'-carbonyldiimidazole.

Nanoparticles consisting of methylprednisolone and this ibuprofen-inulin could be produced, providing an interesting combination therapy for spinal cord injury.⁵⁶ Lastly, it was recently shown that inulin conjugated with diethylenetriamine might be suitable as a carrier for therapeutic delivery of small interfering RNAs.⁵⁷

Local drug delivery

Colon targeting

Chemically modified inulin was also applied in controlled delivery to the colon. The mechanism behind colon targeting with inulin is based on the fact that inulin is only significantly hydrolyzed by inulinases produced by bifidobacteria in the colon and not by the digestive enzymes in the upper parts of the gastro intestinal tract.^{50,58,59} This means that gels and coatings of inulin are not hydrolyzed until these reach the colon where they are fermented, resulting in a colon-specific release of incorporated drug. Several reports have described chemically modified methacrylated inulin (IN-MA) for colonic targeting.^{60,61} These modified inulin chains can be covalently cross-linked to each other and optionally in combination with other monomers using free-radical polymerization resulting in the chemical formation of a gel.⁶²

Hydrogel characteristics such as swelling need to be well chosen for controlled release. If the gel swells too much, premature release will occur. On the other hand to achieve a fast enough release in the colon, sufficient swelling is needed to allow for inulinase to access and hydrolyze the inulin.^{61,62} Finding this balance has been proven difficult, but not impossible.⁶² Gels which were co-polymerized with N,N'-bis(methacryloylamino)azobenzene could be degraded both through breakdown by inulinase as well as reduction of the introduced azo group by bacterial strains present in the colon.⁶³ The molecular weight of inulin used is also relevant here, as higher molecular weight inulins form stronger gels and have higher viscosity, in turn influencing their hydrogel characteristics.¹

IN-MA was used for the colonic delivery of bovine serum albumin, with release being mainly dependent on degree of substitution (DS, defined as the amount of methacryloyl groups per 100 fructose units) of inulin and concentration of IN-MA used.^{50,61} Two formulations, one with 27% w/w IN-MA and a DS of 8.1 and another with 22% w/w IN-MA and a DS of 12.1 were most promising for colonic delivery.⁵⁰ Apart from varying DS and concentration of polymer, copolymerization with other monomers, either more hydrophobic or more hydrophilic, could also modify release profiles.⁶² Another approach was to use a two-step chemical modification of inulin with first methacrylic anhydride (MA), followed by succinic anhydride (SA) for a pH-sensitive release. Hydrogels of inuline-MA-SA showed a pH-responsive delivery of ibuprofen and diflunisal.^{64,65} It was also possible to incorporate IgG during the formation of an inuline-MA₁-SA hydrogel, achieving controlled colonic release of the protein.⁶⁶

Also several other attempts have been made to combine the metabolic degradation dependent release of inulin with a pH sensitive release, but without chemical modification and crosslinking. Free films of inulin with several varieties of Eudragit® were produced and evaluated for colonic delivery. Combinations of inulins with Eudragit RS and RL had more potential for colonic delivery than combinations of inulin and other Eudragit types.⁶⁷ An example of a tablet formulation for the delivery of aceclofenac to the colon that has been shown to be successful in an *in vivo* study is based on a combination of the pH independent Eudragit® RS100 and inulin.⁶⁸

Recently some non-gel colonic delivery systems based on modified inulin have been described. Inulin chemically bonded with cinnamate was used to form drug containing vesicles for colonic targeting. The cytostatic methotrexate was successfully encapsulated in these inulin cinnamate vesicles. However, this system showed a methotrexate release of 30-40% in 24 hours even in the absence of inulinase.⁶⁹ This is undesirable for a cytostatic agent. Another way to produce inulin particles for colonic targeting is by electrospraying inulin. To make inulin suitable for electrospraying it was first acetylated. Particles containing indomethacin produced using this method showed colonic-specific release (by inulinase) *in vitro*.⁷⁰

Pulmonary delivery

Pulmonary administration of drugs is often desirable for pulmonary diseases and it can also be a good route for systemic drug administration. The aerodynamic particle size (APS) of the inhaled aerosol is of great importance for pulmonary delivery. An APS of 1-5 μm is considered essential to obtain an adequate lung deposition.²⁸ Both spray drying and spray-freeze drying can be used to produce particles with a broad APS distribution, allowing targeting of the airways. As mentioned in section *Protein stabilization*, inulin containing formulations have been used to stabilize a vaccine and other proteins during spray drying and spray-freeze drying.

A spray-freeze dried influenza subunit vaccine stabilized by inulin was suitable for inhalation and induced systemic, mucosal, humoral and cell-mediated immune responses in mice after pulmonary administration.²⁸ Inhaled spray dried and spray-freeze dried influenza subunit vaccines formulations induced higher serum IgG titers than intramuscular administration.²³ Influenza whole inactivated virus vaccine spray freeze-dried with inulin was also safe and efficient for pulmonary immunization.⁴⁰ Combined with the improved storage stability pulmonary administration of inulin stabilized dry powder influenza vaccines seems promising.^{23,40} Inulin is thus a suitable stabilizer for dry powder formulations of vaccines for pulmonary administration.⁷¹

Spray freeze-drying of acyl-homoserine lactone acylase PvdQ, an enzyme that can be used in the treatment of *Pseudomonas aeruginosa* infections, with either trehalose or inulin

produced stable formulations. The powder particles had an average aerodynamic diameter of $\sim 1.8 \mu\text{m}$, indicating they would be suitable for inhalation and might be used in the treatment of chronic infections in cystic fibrosis patients.²⁹ Another example of a therapeutic spray-freeze dried with inulin is cyclosporine A, which might be used to prevent allograft rejection for lung transplant patients.⁷² Using spray-drying, an inulin-based formulation of rhDNase was produced with a mass mean aerodynamic diameter of $2.3 \mu\text{m}$, making it a suitable therapeutic for patients with cystic fibrosis.³⁰ Lastly, inulin-stabilized spray freeze-dried particles containing THC were also suitable for inhalation.⁴²

PHYSIOLOGICAL AND DISEASE-MODIFYING EFFECTS

Systemic

Vaccine adjuvant

Apart from being a suitable stabilizer of vaccines, several papers have reported an adjuvant role of inulin in obtaining an immune response upon vaccination. Mostly the crystalline types of inulin, γ - and δ -inulin, which are virtually insoluble at 37°C , were used. These crystalline forms consist of inulin with a relatively high molecular weight, the more soluble α and β forms also contain lower molecular weight inulin fractions.⁷³ More information on the different subtypes of crystalline inulin can be found in the first part of this review.¹ It was shown that γ -inulin enhances both humoral and cell-mediated immune responses in various animal models for a wide variety of antigens, making it a very interesting adjuvant for vaccines.^{74,75} Cooper & Carter (1986)⁷⁶ reported γ -inulin specifically activates the alternative complement pathway, whereas the more soluble isoforms of inulin, α and β , were found to be biologically inactive and even hindered pathway activation by γ -inulin. The δ -inulin isoform had not been discovered at that time, but most likely acts as an adjuvant according to the same mechanism as γ -inulin.

It was found that δ -inulin was more immunoactive than γ -inulin.⁷⁷ Thus far, it has for example been applied to enhance the potency of a trivalent human seasonal influenza vaccine in mice⁷⁸, split-virion H5N1 influenza in ferrets⁷⁹, a pulmonary formulation of whole inactivated H1N1 influenza vaccine in mice⁸⁰, and hepatitis B in mice, guinea pigs and humans.^{81,82} It was also shown that co-administration of δ -inulin with inactivated H1N1 influenza vaccine achieved a better immune response in pregnant mice, both for the mother and the pups.⁸³ In contrast to the above, Kumar & Tummala (2013)⁸⁴ have reported that it is possible to use soluble inulin for both vaccine stabilization and as an adjuvant. They developed soluble inulin microparticles which they loaded with ovalbumin and achieved a robust immune response, outperforming antigens adjuvated by traditionally used aluminum salts. It would be interesting to see further research to confirm that soluble inulin can also be an adjuvant and if confirmed, further investigation into the mechanism behind turning soluble inulin into an adjuvant.

Kidney function

A widely established application of inulin is as a diagnostic for kidney function testing, for this application inulin is intravenously injected. Inulin is highly suitable for this application because it is distributed over the extracellular volume only and it is not metabolized. Furthermore it is only excreted via glomerular filtration and not resorbed by renal tubules. This makes it the most accurate substance for determination of glomerular filtration rate.⁸⁵ The test can be executed by administering inulin as a bolus or constant infusion and measured concentrations of inulin in both urine and plasma can be used for the determination of the filtration rate.⁸⁶ Because inulin is filtered out freely because it is relatively small, the excretion rate is directly proportional to the glomerular filtration rate.⁸⁵ As the kidneys do resorb water, the ratio between the concentrations of inulin in the tubular fluid plasma can be used to determine water resorption in the kidney.⁸⁷ However, a drawback of this method is the detection of inulin in biological matrices.⁸⁵ Several analytical techniques have been described in literature, but care should be taken in comparing results from different analytical methods as differences are not always negligible.⁸⁸

Gastro-Intestinal tract***Constipation***

Inulin is widely used as a dietary fiber and prebiotic in so-called functional foods. These uses are worth mentioning in this context, but are not pharmaceutical applications and we will thus suffice by referring to some reviews on this topic. Flamm *et al.*⁵⁹ reviewed inulin as a dietary fiber, Kolida, Tuohy, & Gibson (2007)⁸⁹ made a comprehensive overview of the prebiotic effects of inulin and oligofructose and lastly Kelly (2008, 2009)^{90,91} produced an extensive two-part review about inulin-type prebiotics also in relation to some physiological effects. Nutrition can be used to provide health benefits by modification of gut microbial flora.⁹² In fact, inulin's effect on gut flora and gut mobility has been linked to a variety of beneficial effects, both local and systemic.⁹³ Inulin, in particular high molecular weight inulin, increased stool frequency and can thus be used against constipation.⁹⁴ It has been shown to improve stool frequency in formula fed newborns, creating a gut microbiota closer to that associated with breastfeeding.⁹⁵ Inulin was also able to relieve constipation in elderly patients, indicating that the stool promoting effect of inulin is present for all ages.⁹⁶

Inflammatory bowel disease & colon cancer

Oral administration of inulin has been reported to achieve both local and systemic immune modulation. A review of the supporting evidence concluded that the local immunomodulatory effect is apparent, but systemic effects are less substantiated.⁹⁷ The local effect is possibly indirect through the prebiotic action of inulin, stimulating growth of beneficial bacteria in the gut.^{98,99} In a later *in vitro* study, it was found that inulin also possesses direct signaling

capacity on human immune cells, mainly through the toll-like receptor 2.¹⁰⁰ It is conceivable that these local effects could be beneficial to patients suffering from inflammatory bowel disease and irritable bowel syndrome.¹⁰¹ Thus far, investigations with small numbers of patients have reported mixed results in this regard and there is thus a need for further investigation of this potential application of inulin.^{91,102}

Inulin was able to reduce chemically induced pre-neoplastic lesions or tumors in the colon of mice and rats.^{103,104} Long chain inulins were more potent than smaller chain inulins in this sense. This reduction was associated with the gut flora-mediated fermentation of inulin.¹⁰³ In a recent study in rats, inulin showed to have a bigger prophylactic potential to colon carcinogenesis compared to lactulose.¹⁰⁴ Inulin reduced cytotoxicity and genotoxicity *in vitro* in human colon adenocarcinoma cells.¹⁰⁵ Again these results seem promising, but further clinical research is required to see if these results can be reproduced *in vivo* in humans.

OVERVIEW

In this chapter the pharmaceutical applications of inulin, an oligosaccharide being increasingly used in food, pharma and other fields, have been reviewed. The most widely established use of inulin in pharma is as a diagnostic to determine kidney function. Inulin's chemical structure makes that it is not metabolized by the body and excreted completely via glomerular filtration. Gut microbiota, however, are able to metabolize inulin. This makes inulin suitable for colon specific drug delivery and as a prebiotic. There is some evidence that inulin's prebiotic characteristics also lead to health benefits, particularly for patients with inflammatory bowel disease or in prevention of colon cancer. These claims, however, need further evidence.

Solid dispersions of amorphous inulin can be used to improve the dissolution behavior of lipophilic drugs. Amorphous inulin was shown to be a suitable stabilizer for membranes and proteins, protecting them against drought and elevated temperatures. Inulin has not yet been used in commercial formulations for this purpose but as the number of new biopharmaceuticals keeps increasing, it could be an interesting new stabilizer. In addition, insoluble isoforms of inulin have an adjuvant effect on the immune response achieved with several vaccines. Inulin could therefore serve two purposes as an excipient for vaccines, achieving both stabilization and an increased effectivity. Overall the uses of inulin are already diverse. Additionally more and more research is being done with chemically modified inulins, making it likely that more applications will be found for this flexible oligosaccharide.

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